ENVIRONMENTAL GEOLOGY NOTES

APRIL 1975 • NUMBER 74

STUDIES OF LAKE MICHIGAN BOTTOM SEDIMENTS—NUMBER TWELVE

A SIDE-SCAN SONAR INVESTIGATION OF SMALL-SCALE FEATURES ON THE FLOOR OF SOUTHERN LAKE MICHIGAN

Jonathan M. Berkson

Formerly, Geophysical and Polar Research Center
University of Wisconsin, Madison
At present, U.S. Naval Oceanographic Office
Washington, DC

Jerry A. Lineback and David L. Gross

Illinois State Geological Survey

UNIVERSITY OF WISCONSIN
GEOPHYSICAL AND POLAR RESEARCH CENTER CONTRIBUTION 301

ILLINOIS STATE GEOLOGICAL SURVEY

Jack A. Simon, Acting Chief • Urbana, IL 61801

A SIDE-SCAN SONAR INVESTIGATION OF SMALL-SCALE FEATURES ON THE FLOOR OF SOUTHERN LAKE MICHIGAN

Jonathan M. Berkson[1], *Jerry A. Lineback*[2], *and David L. Gross*[2]

ABSTRACT

Side-scan sonar was used in conjunction with high-resolution seismic profiling, acoustic depth recording, and sediment sampling to study small-scale features on the floor of southern Lake Michigan. Deep-water lacustrine clays in the lake are characterized by low backscattering levels because of their low acoustical impedance contrast with water. Oval depressions 30 to 50 m (98 to 164 ft) in diameter and 2 m (6.6 ft) deep occur in the thick clay sequence. Nearshore, sand occurs in bars, ripples, and sheets. Areas of rocky and bouldery bottom were identified near Chicago. Sandy silt bottoms occur near Benton Harbor, Michigan; they are smooth except for individual points of high backscatter that are of unknown origin. Parallel linear ridges of till or sand with relief of as much as 3 m (10 ft), spacings of 230 to 880 m (755 to 2,887 ft), and lengths in excess of 1,800 m (5,905 ft) are found in water of 8 to 30 m (26 to 98 ft) depth. These features may be glacial grooves or sand waves. Their orientation is generally north-south, parallel to the long axis of the lake basin.

[1] Formerly, University of Wisconsin, Madison, Geophysical and Polar Research Center; at present, U.S. Naval Oceanographic Office, Washington, D.C.

[2] Illinois State Geological Survey, Urbana, Illinois.

INTRODUCTION

Side-scan sonar was used to study small-scale features on the floor of southern Lake Michigan. The study was conducted in October 1972 from the Research Vessel *Inland Seas* by the Illinois State Geological Survey and the University of Wisconsin Geophysical and Polar Research Center. The side-scan sonar instrument displays the geographic location of bottom features that scatter sound. It is particularly useful for studying lake-bottom features of a scale intermediate between the very small features observed in bottom photographs and the larger features delineated by vertical echo sounding. Bottom samples, high-resolution 3.5 kHz subbottom profiles, and 25 kHz vertical echo sounding data also were obtained in this survey of southern Lake Michigan.

Acknowledgments

We appreciate the cooperation and assistance of Captain Richard Thibault and the crew of the R. V. *Inland Seas*. The University of Michigan Great Lakes Research Division operated the ship under a grant from the National Science Foundation. The participation of the University of Wisconsin Geophysical and Polar Research Center was sponsored by the Office of Naval Research.

EQUIPMENT

Echo Sounder

The recording echo sounder of the ship is a Raytheon fathometer, Model DE-714/715. The frequency is 25 kHz and the pulse length is 0.25 msec for operation on the 0 to 300 ft (0 to 91.4 m) scale and 3 msec for the 240 to 540 ft (73.2 to 164.6 m) scale. The beam width to the -6 dB level is 25°.

Side-Scan Sonar

The side-scan sonar instrument used in this study is a modified Kelvin Hughes Transit Sonar Model MS43 Mk 1. The frequency is 48 kHz and the pulse length is 1 msec. The beam width to the -3 dB level is 1.5° horizontally and 51° vertically. The instrument's transducer was mounted on an outboard rig on the side of the ship, 2 m (6.6 ft) below the water level. The maximum range of the instrument can be set at 225 or 550 m (738 or 1,804 ft). During this survey, the 550 m (1,804 ft) range was used. Approximately 416 km (258 mi) of side-scan sonar tracks were obtained during the October 1972 cruise. This amounts to sonar images of about 229 sq km (88 sq mi) of the floor of southern Lake Michigan.

PRINCIPLE OF THE SIDE-SCAN SONAR

In contrast to the echo sounder, which has a conical transmitting and receiving intensity pattern, the side-scan sonar has a beam pattern that is fan-shaped, that is, narrow horizontally and wide vertically (fig. 1). Thus, the sound will intersect the lake bottom only in a long, narrow strip that is perpendicular to the ship's track. As the sound wave grazes the bottom and encounters rough features, the sound is scattered in many directions. Some of the energy is scattered back toward the transducer, where it is received, and the relative intensities versus elapsed time are recorded on a graphic recorder in the ship's laboratory. A time-variable gain is used to compensate for the decrease in signal level as the range increases. Each line of the graphic sonar record represents the intersection of the sound beam with the lake floor. Thus, as the ship advances, a graphic picture of the lake floor is constructed one line at a time into a side-scan sonar record called a sonograph.

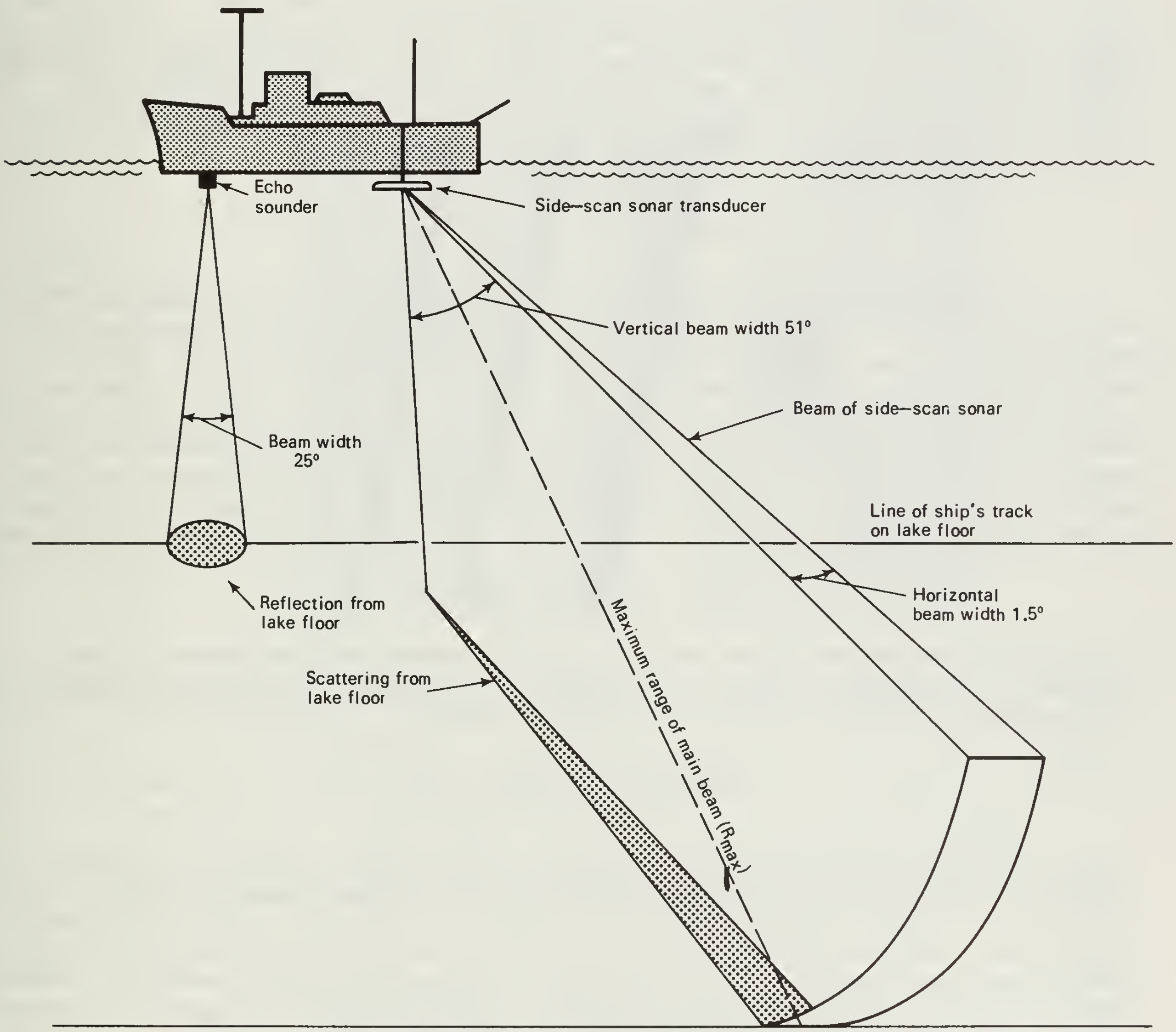

Fig. 1 - Diagram of the beams of the echo sounder and the side-scan sonar.

The sonograph is a map-like image of the pattern of scattering of acoustical signals reflected from the lake bottom. Differences in scattering may be due to changes in bottom type, in local bottom roughness, or in total relief. Simultaneous echo sounding records and bottom samples are important aids in analyzing sonographs. In areas of the lake bottom where there are changes of bottom type in short distances, it is important to identify which bottom type the samples represent. This identification may be done with a hull-mounted side-scan sonar, which sounds in a known direction with respect to the stationary ship. If the orientations of the vessel and the time of the sampling are marked on the sonograph, the bottom type of the sampling station can be identified.

INTERPRETATION OF SONOGRAPHS

Sonograph interpretation is only briefly reviewed here. For more detail the reader should refer to Chesterman, Clynick, and Stride (1958); Stride (1961); Clay, Ess, and Weisman (1964); Tucker (1966); Sanders and Clay (1968); and Mudie, Normark, and Cray (1970). The sonograph is a graphic record of a plan view of bottom features that scatter sound. However, several factors may result in distortions on the sonograph.

Lateral-Scale Distortion

The range of the sonar, R_{max}, is the maximum travel distance of the sound during one sonar sweep, and is constant for a given range setting of the recorder. R_{max} is represented by A on the sonograph (fig. 2). Let B on the sonograph (fig. 2) represent the movement of the ship in the direction of travel for a distance equal to R_{max}. For a given recorder paper speed, the distance on the lake floor represented by B on the sonograph depends on the speed of the ship. If A/B is not 1, the record will be stretched in one dimension and the shapes of features will be distorted. For example, in figure 2, the apparent angle, θ_a, is related to the real angle, θ, by the relationship:

$$\tan \theta = (A/B) \tan \theta_a.$$

This distortion may be corrected by optically squeezing the record in one dimension. Sonographs shown in this paper are slightly distorted by being compressed in the direction of the ship's movement.

Slant-Range Distortion

Figure 2 shows that a distortion of the plan display of bottom features occurs because the data are displayed in slant range (distance between the side-scan sonar transducer and the acoustic reflector on the lake floor, R_{max}, equals maximum slant range). The distortion is greatest at close ranges and can be corrected by a series of optical squeezes (Berkson and Clay, 1973a). Beyond the range of several times the water depth, the true range (distance between the projection of the ship's track on the lake floor and the acoustic reflector on the lake floor) is about equal to the slant range. For example, if the true range is equal to 3 times the water depth, the error in using slant range is

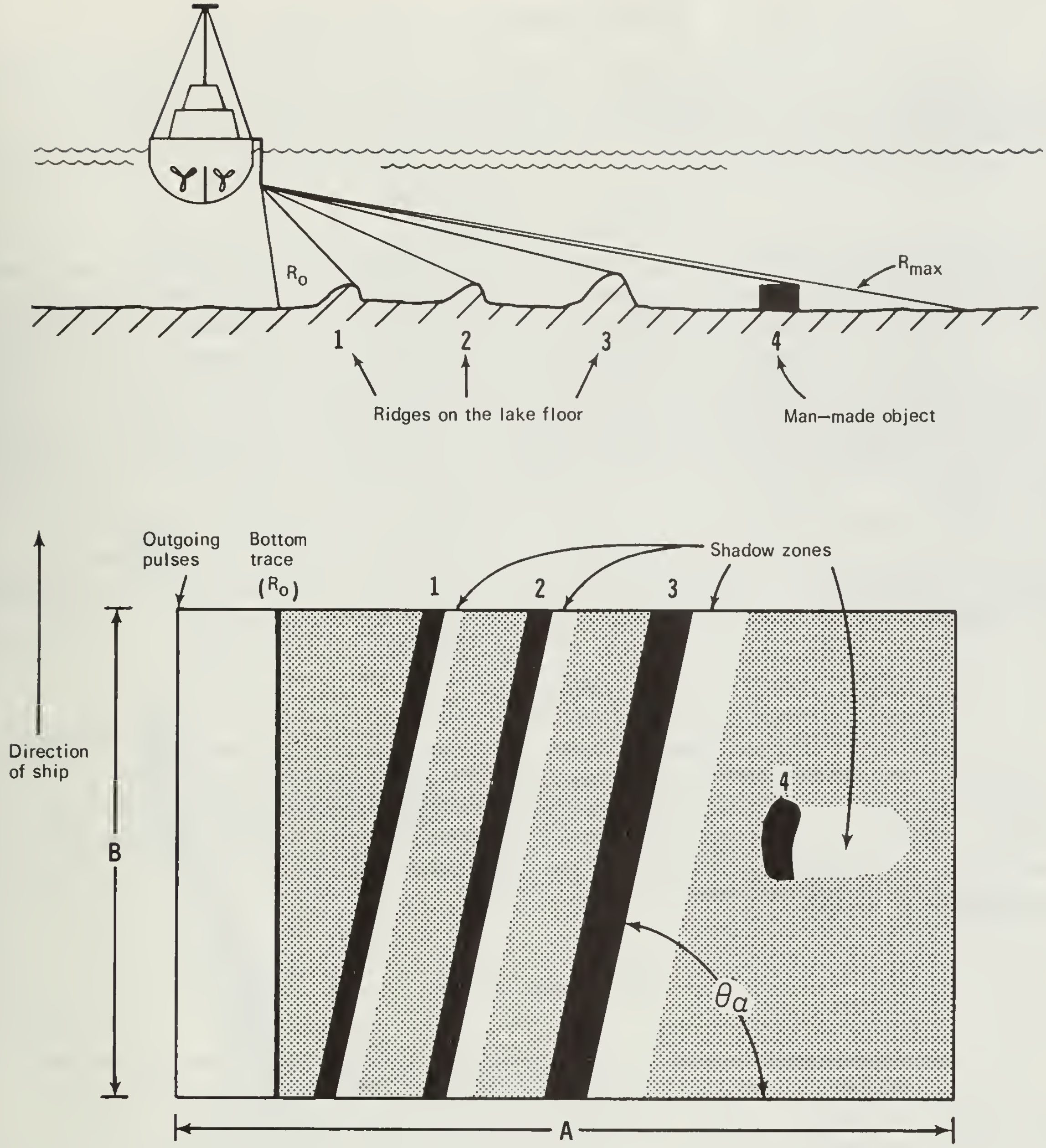

Fig. 2 - Relationship between the lake bottom and the sonograph. The sonograph is a plan map of the acoustic scattering from the lake bottom from the bottom-reflected ray, R_o, to the ray R_{max} received at the maximum range of the sonar. The light-tone background on the sonograph is due to the backscattering of sound from very small irregularities in the bottom. The shadow zones are caused by the absence of backscattering where sound is blocked by obstacles. The location of features in the near range of the sonograph (e.g., between R_o and 1) is distorted because of the slant-range presentation. The geometry of slant-range presentation is discussed in the text.

about 6 percent, and if true range is more than 7 times the water depth, the error is less than 1 percent. The distortion was not a problem in this survey because the data were taken in relatively shallow depths (that is, water depths generally less than 50 m [164 ft]), with a 550 m (1,804 ft) range setting on the instrument.

Refraction

Refraction of sound due to changes in sonic velocity with depth and temperature may result in slight distortion of the record. This effect is negligible for this survey.

Movement of the Ship

For the side-scan sonar instrument to generate a correct display of the bottom, its transducer must move at a constant speed and direction. The display is distorted during changes of speed or during a change of course. Record sections of constant speed may be identified by frequently marking the time of navigation fixes on the sonograph. The small changes of course during the steering of a vessel will result in a loss of resolution of features, but normally the loss will not be significant. The effect is greater in a hull-mounted transducer than in one on a towed "fish," which smooths out the small course changes. A distortion also occurs when the ship heads in a direction significantly different from the actual course (for example, when traveling in strong winds or currents), because the hull-mounted transducer always transmits perpendicular to the axis of the vessel. Pitching and rolling have little effect on the display because of the fan shape of the beam.

Artifacts

Various artifacts may appear on sonographs. Some are the result of problems with the recording technique such as improper adjustment of the time-variable gain, electrical noise, or difficulties with the mechanical recorder. Others are due to acoustical phenomena such as reflections from the water-wave surface, acoustic noise, and interference between the direct and the surface-reflected sound waves.

BOTTOM SEDIMENTS

The stratigraphy and bottom sediments of southern Lake Michigan have been described in detail by Gross et al. (1970); Lineback, Ayer, and Gross (1970); Lineback et al. (1971); Lineback, Gross, and Meyer (1972); and Lineback and Gross (1972). Previously data had been reported by Hough (1935); Ayers (1967); and Somers and Josephson (1968). Shoreline or very shallow water studies were made by Davis and McGeary (1965); Hawley and Judge (1969); and Hands (1970). Gross et al. (1972) discussed the composition of Pleistocene sediments under Lake Michigan. Collinson and Badal (1972) studied the composition of the uppermost few centimeters of sediment on the lake floor. Fraser and Hester (1974) discussed the thickness of sand on the lake floor along the northern Illinois lake shore.

The surficial sediments in the deep water near the center of the lake basin are clay or silty clay. Nearshore areas, where wave and current action impinge on the lake floor, have coarser sediments—silt, sand, or gravel—mantling the underlying deposits. A large area of the lake floor near Chicago is irregularly covered by thin sand and gravel over glacial till. Normal bottom-sampling programs do not show the relationship of these materials to each other. The sonographs, however, do show the relationship of the sands and gravels to each other and to the bottom topography.

SMALL-SCALE FEATURES OBSERVED UNDER LAKE MICHIGAN

The side-scan sonar and echo sounding tracks are shown in figure 3. The records show that the different bottom sediment types each have associated distinctive small-scale topographic features. The distribution of small-scale features also is shown by figure 3.

The character of echograms (records of the vertical echo sounder) has been used to correlate surficial bottom deposits between sampling stations in Lake Michigan (Hough, 1952, 1955). We found that the echograms reliably indicated the presence of soft clay bottom or sand bottom but did not reliably distinguish between till bottom and sand and gravel bottom.

The spatial relationships of the bottom types shown on the sonographs are often complex, but flat sand is characterized by medium, even backscattering and sand ripples and gravel bottom by higher backscattering.

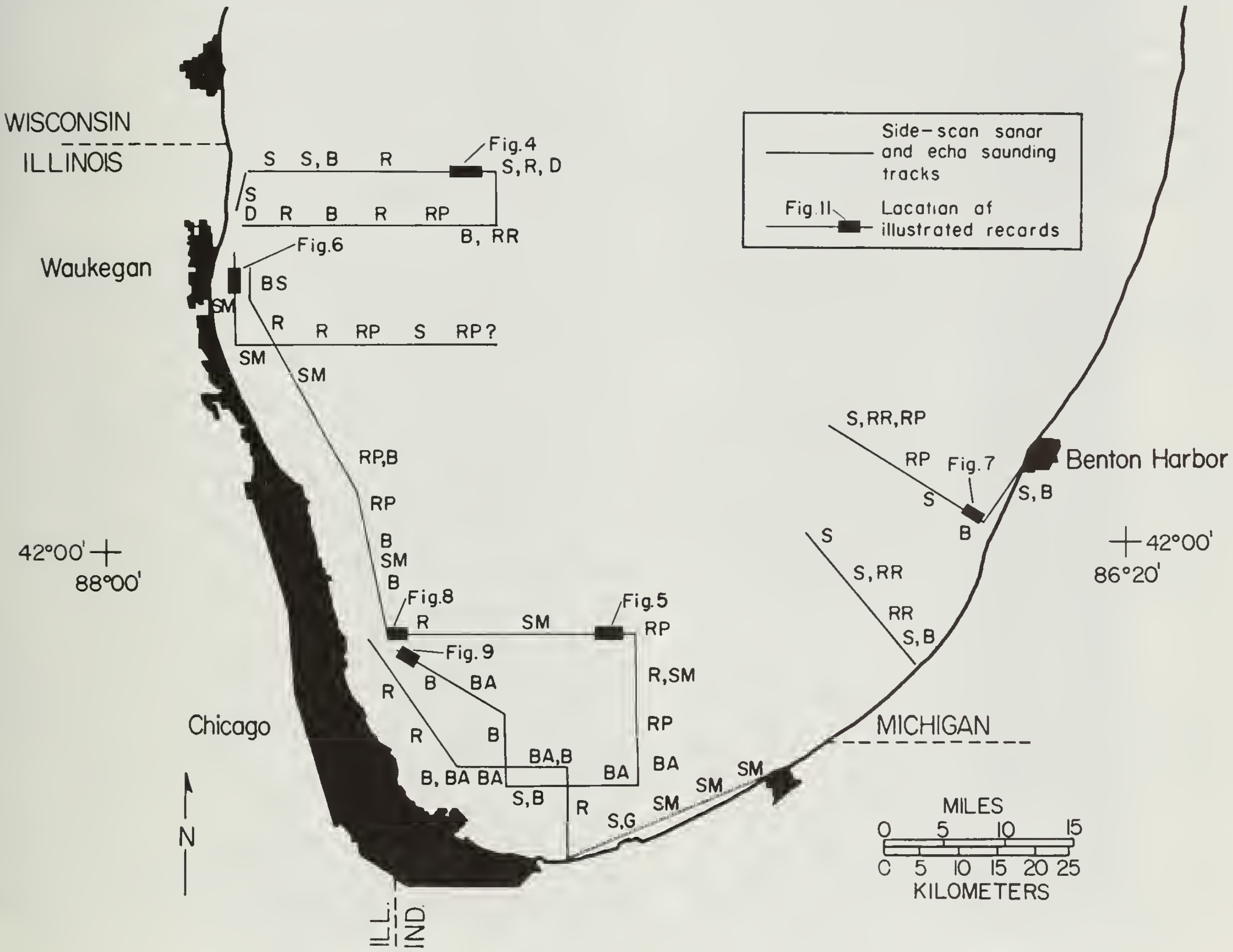

Fig. 3 - Map of southern Lake Michigan showing lines of side-scan sonar tracks, small-scale bottom features encountered along the tracks, and location of illustrated sonographs. Symbols: BS - blanket sand; R - linear sand ridges; SM - irregular sand cover; RP - ripples in sand; B - boulders; S - smooth bottom; D - oval depressions; RR - discrete reflectors of unknown origin, possibly boulders or fish; BA - banding by small ridges or megaripples; G - grooves and/or other linear depressions in till.

Sonographs of the deep-water lacustrine clays near the center of the southern lake basin (fig. 4) are characterized by low backscattering levels. This is probably due to the relative smoothness of the soft clays and to their low acoustical-impedance contrast with water. In these areas the bottom is generally without significant features, but in some areas there are relief features of small, separated oval depressions with dimensions of 30 to 50 m (98 to 164 ft), separations of 10 to 600 m (33 to 1,968 ft) and relief of up to 2 m (6.6 ft) (fig. 4). The horizontal arrows on the sonograph point to the oval depressions; and the vertical arrows on the echogram point to similar features that the ship passed over. The features are similar to some members of a group of relief features in the soft, water-saturated lacustrine clays in Lake Superior that are believed to be the result of syneresis (Berkson and Clay, 1973b; Berkson and Clay, 1973c).

Other bottom features can be seen in sandy sediments of shallow-water areas. Sand occurs in sheets, bars, ripples, and patches. The patches show up as light-colored features on the sonographs. Large-scale ripples (fig. 5) occur in places near the southern end of the lake. These ripples have wavelengths of up to 40 m (131 ft) and an unknown amplitude, and individual ridge crests can be traced for 300 m (984 ft). Sand ripples of this magnitude at a depth of 30 m (98 ft) indicate considerable current activity. The ripples in figure 5 are oriented northwest-southeast. In some places, areas of rocks and bouldery bottom can be distinguished.

A sonograph from shallow water near Waukegan (fig. 6) shows flat sand (light areas) characterized by medium, even backscattering. The darker mottled areas indicate greater backscattering from gravel or outcrops of till. Linear features, possibly large ripples, are oriented northeast-southwest.

Sandy silt is found nearshore near Benton Harbor, Michigan (fig. 7). It has an even pattern of backscattering except for individual points of higher intensity. The bottom appears to be covered with boulders; however, the size of these features is 3 to 6 m (10 to 20 ft) in diameter and the presence of boulders or man-made debris of this size has not been confirmed by sampling. These features may be alternately interpreted as schools of fish on or near the bottom.

Groups of parallel linear features (figs. 8 and 9) having vertical relief of 0.3 to 3 m (1 to 10 ft) occur on widespread areas of the lake floor (fig. 10) at water depths of 8 to 30 m (26 to 98 ft). The length distribution was not obtained, because the features were longer than the section mapped by the sonograph. However, the observed segments varied from 550 to 1,800 m (1,804 to 5,905 ft) in length, depending on the angle between the ship's track and the feature. Within a group, the spacing is generally constant, with some features absent or masked. The average spacing in each group of ridges is shown in figure 10. Parallel linear features have been found in areas of till, sand-covered till, and gravel-covered till. In many grab samples, the sand or gravel proved to be a thin veneer over till. High-resolution reflection seismic profile records do not record the topography of the sand-till interface because the 3.5 kHz sound does not penetrate a thin sand covering (Lineback et al., 1971; Lineback, Gross, and Meyer, 1972). However, a mini-boomer seismic profiler using a higher-energy source than that of the high-resolution seismic profiler was operated in conjunction with the side-scan sonar. It indicated that the sand layer is thin, but did not indicate the exact thickness.

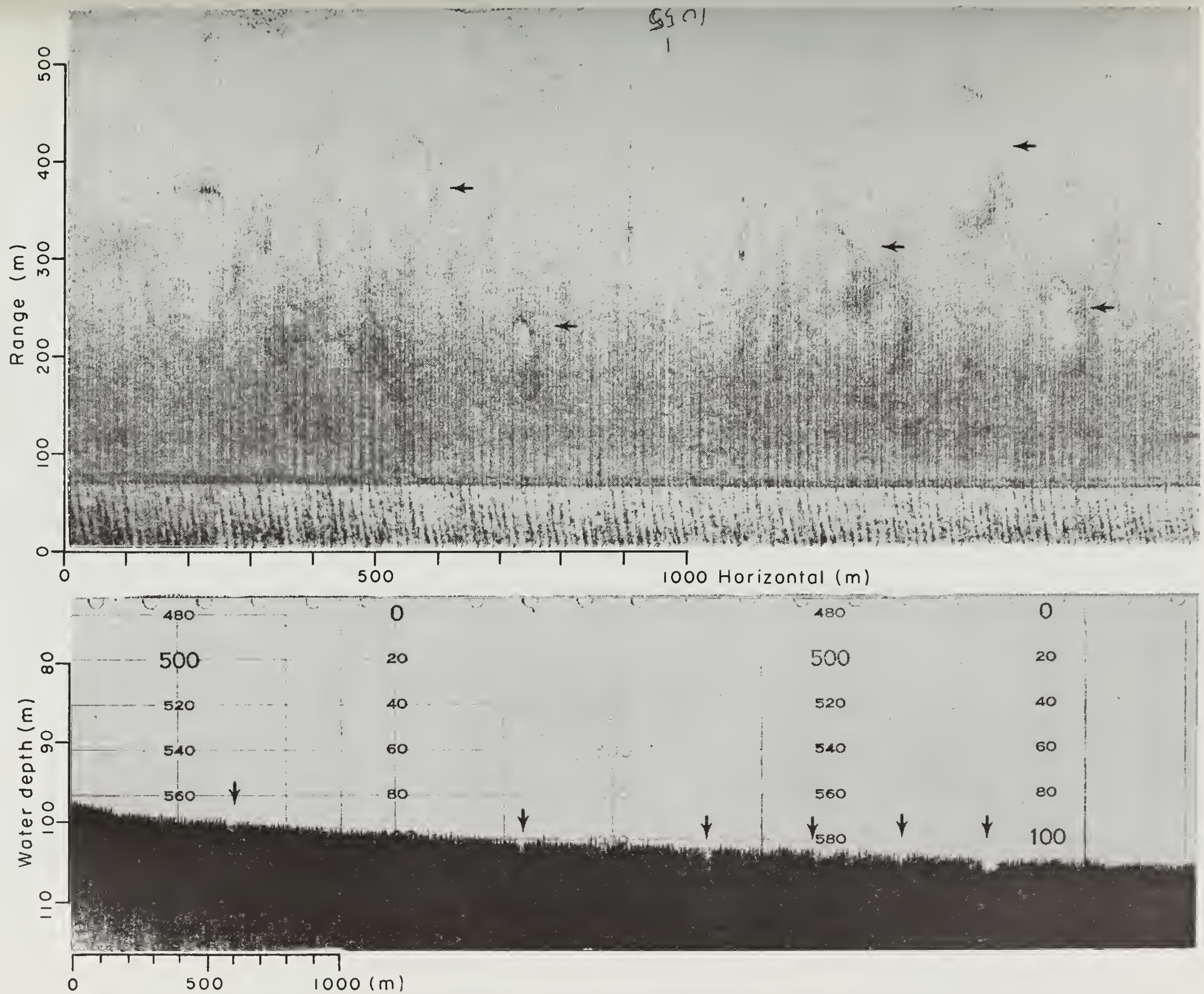

Fig. 4 - Sonograph (top) and echogram (bottom) of clayey sediments 40 km (25 mi) northeast of Waukegan. Arrows point to oval depressions on sonograph and on echogram.

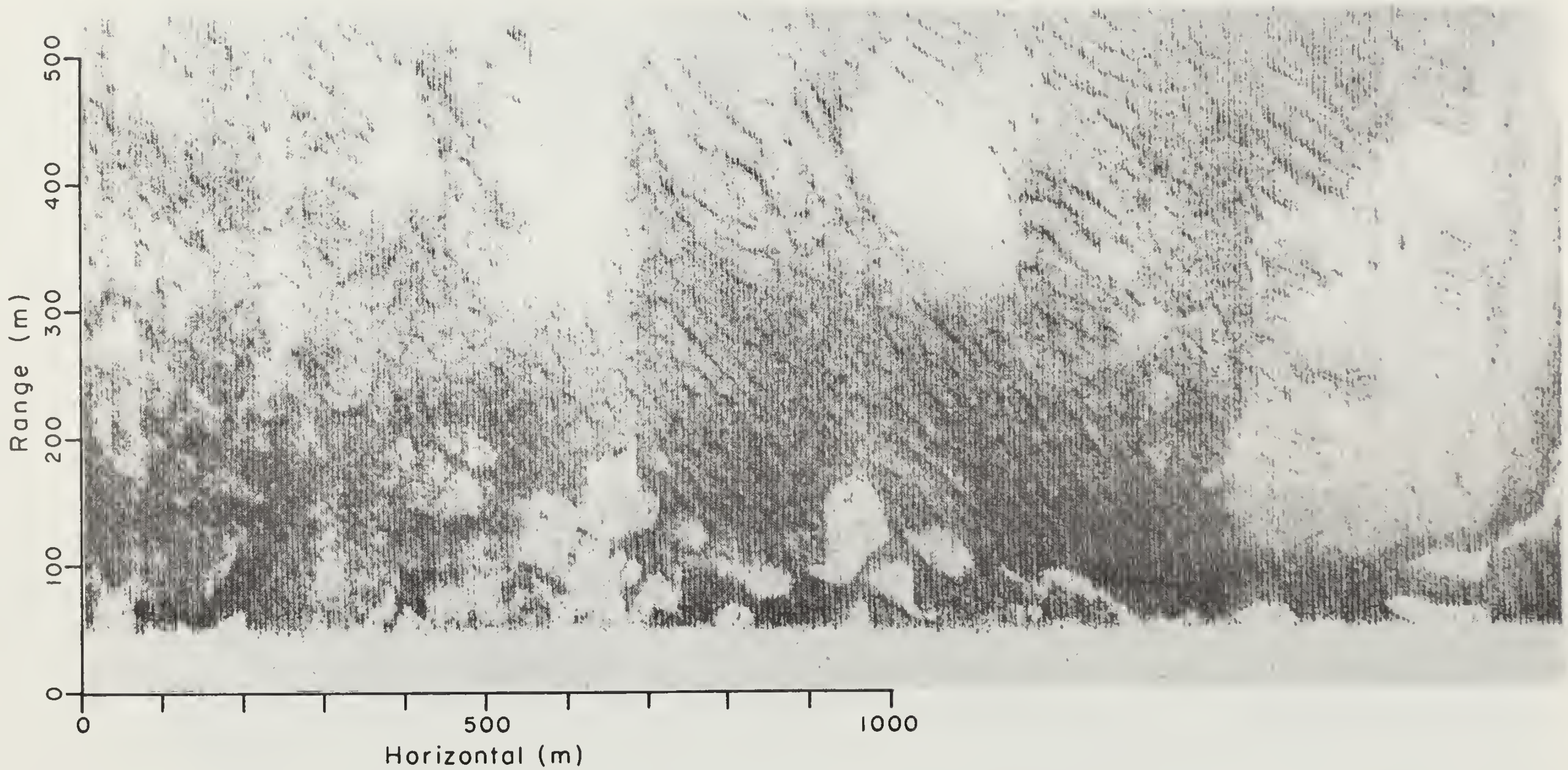

Fig. 5 - Sonograph 40 km (25 mi) east of Chicago that shows large ripples in sand.

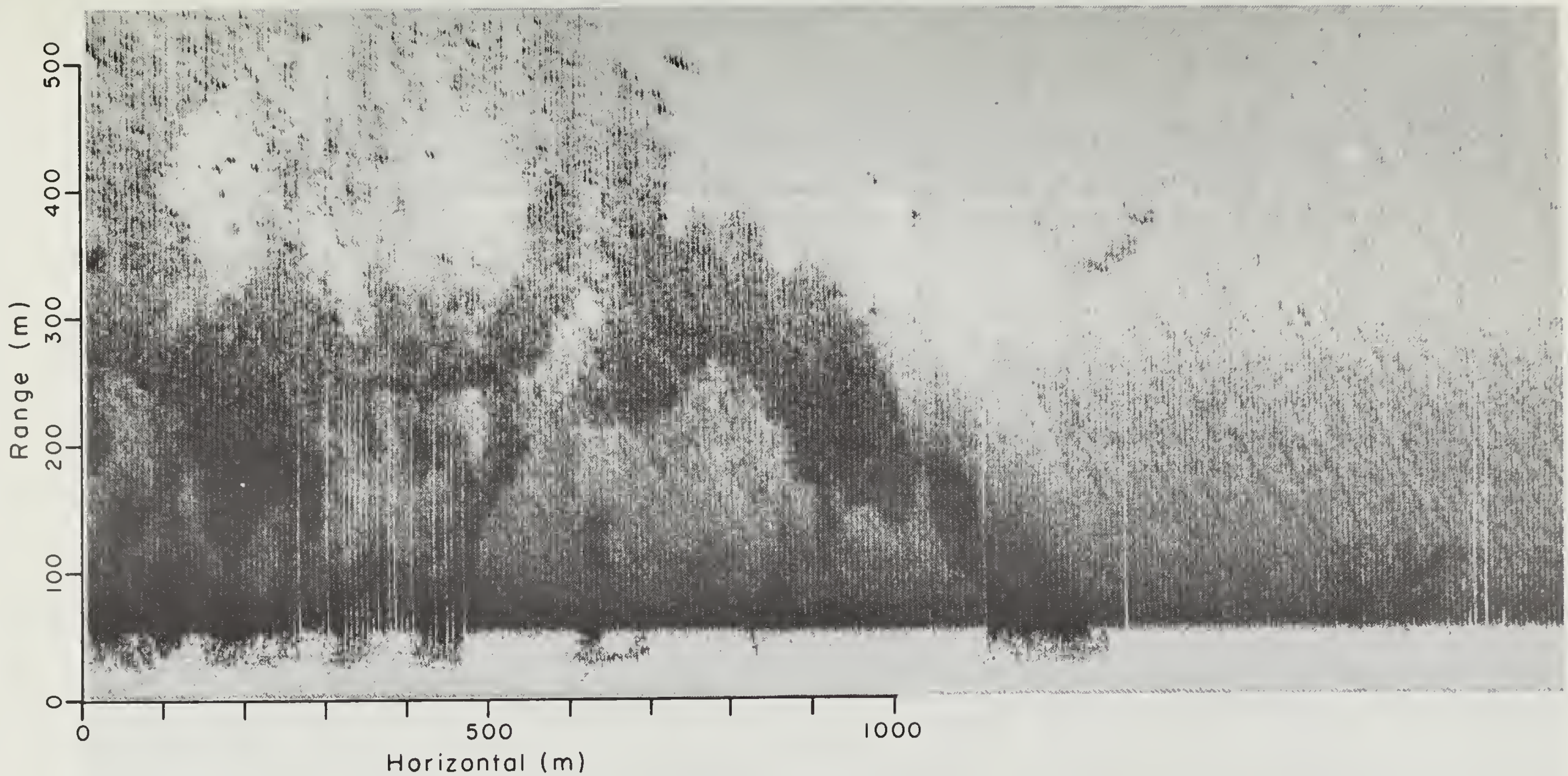

Fig. 6 - Sonograph 3 km (1.9 mi) east of Waukegan showing sand patches and linear sand features.

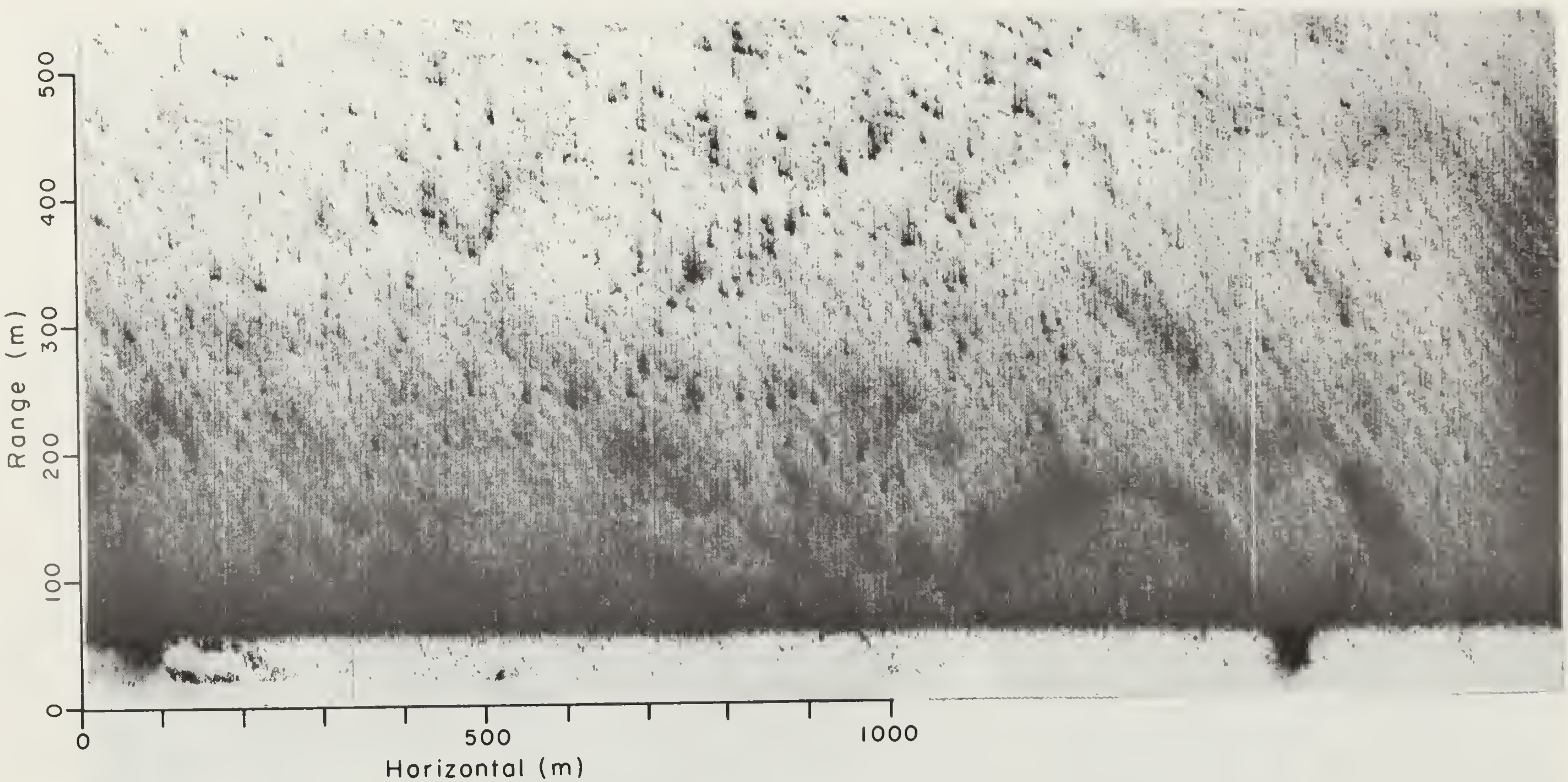

Fig. 7 - Sonograph 10 km (6.2 mi) southwest of Benton Harbor, Michigan, showing discrete features, which may be boulders or man-made debris on the lake floor or schools of fish.

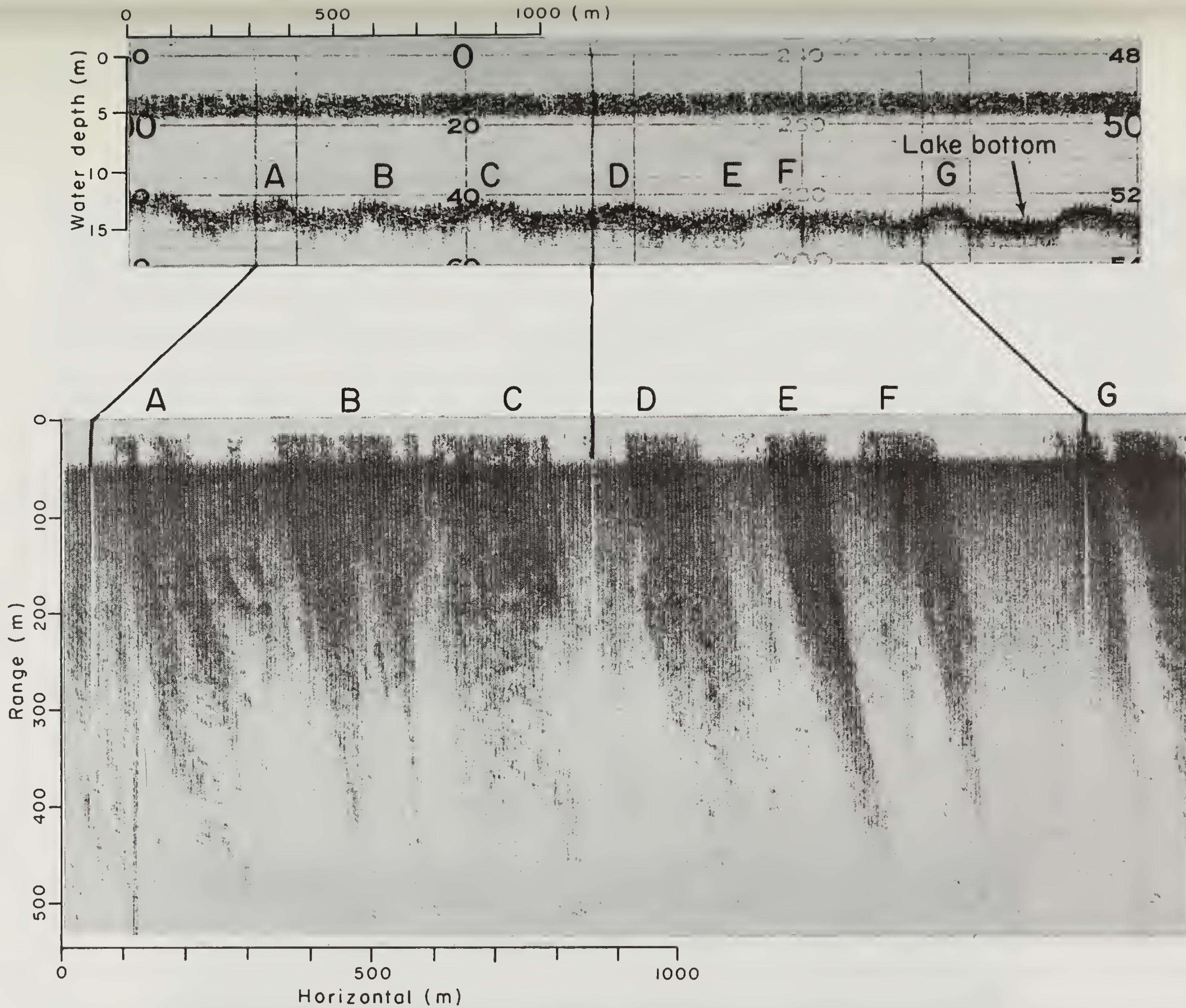

Fig. 8 - Sonograph (bottom) and corresponding vertical echogram (top) from 7 km (4.3 mi) east of Chicago showing linear ridges on the lake floor. Ridges A through G are correlated between the sonograph and the echogram. The echogram shows water depth and lake floor relief directly beneath the ship's track.

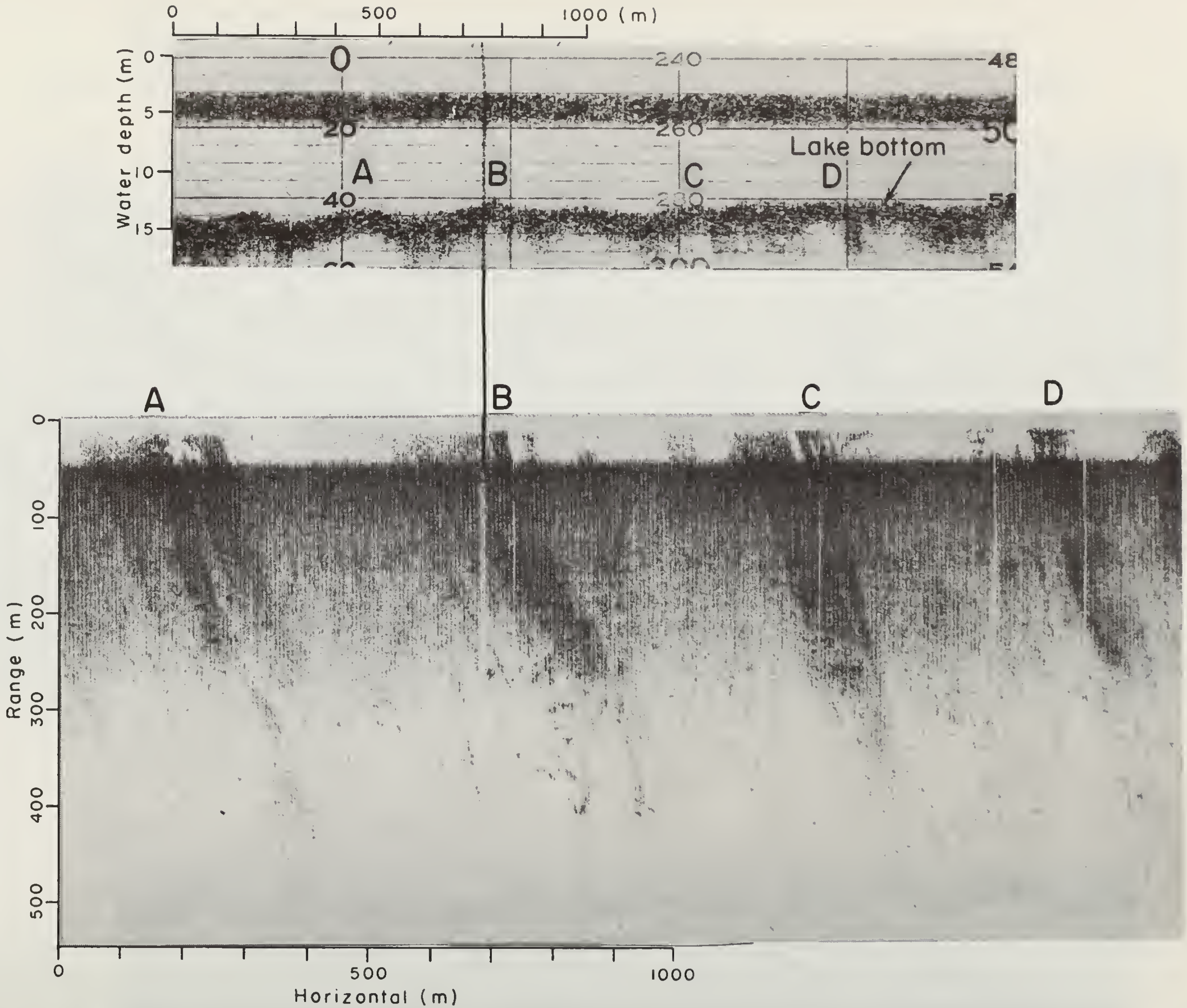

Fig. 9 - Sonograph (bottom) and corresponding vertical echogram (top) from an area 7 km (4.3 mi) east of Chicago showing linear features like those in figure 8. The ridges A through D are correlated between the sonograph and the echogram. Spacing is wider than that in figure 8.

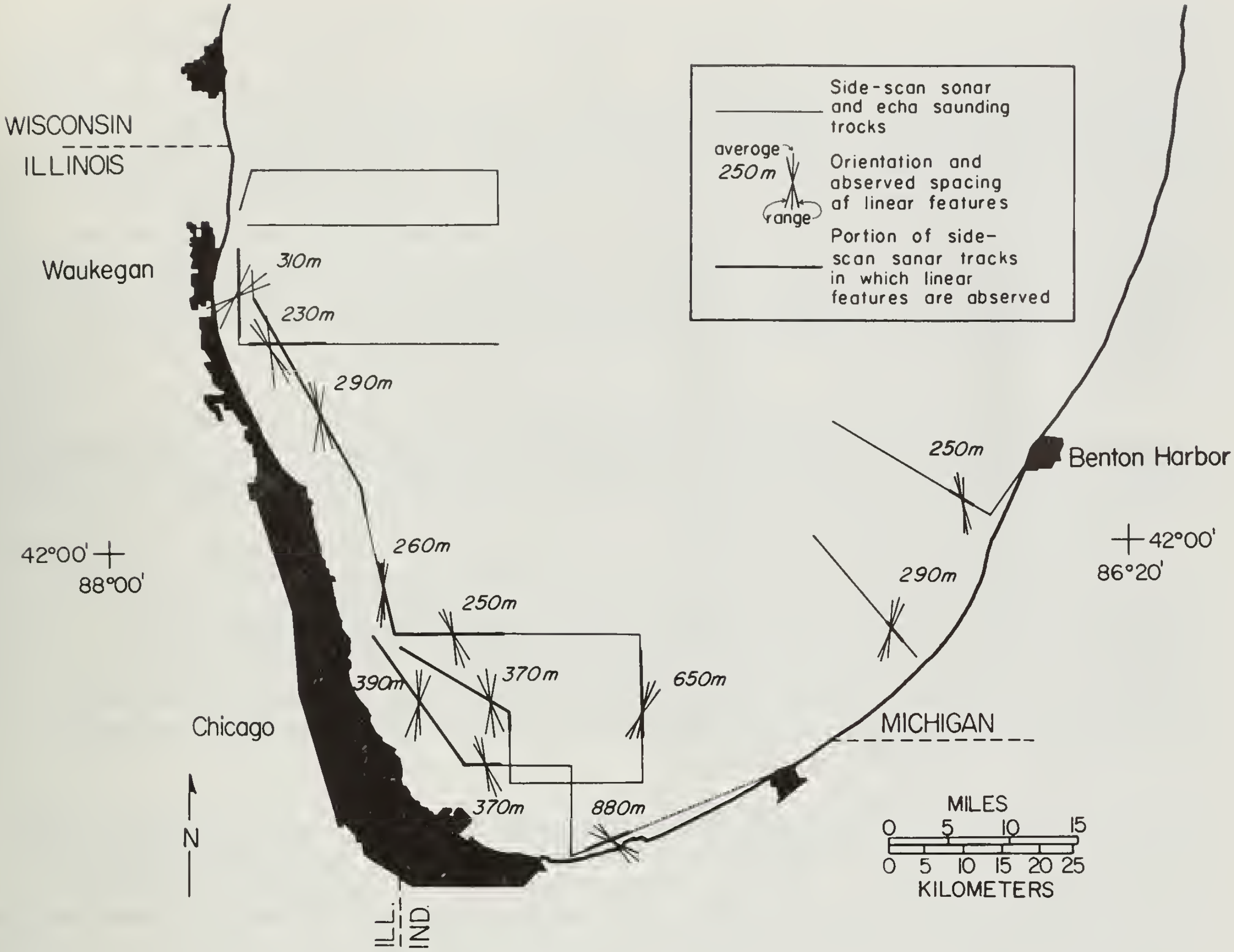

Fig. 10 - Map showing location, orientation, and spacing (meters) of linear ridge features on the floor of Lake Michigan. The orientations have been corrected for lateral-scale distortion.

Thus, the origin of the surface features remains undetermined, although they have some of the same characteristics as glacial flutings, offshore bars, and sand waves. The group parallelism, regularity of separation, and wave-like relief are typical of glacial flutings. The spacing is typical of flutings made by continental glaciers in Alberta, Canada (Gravenor and Meneley, 1958) and in northern Michigan (Hack, 1965).

Nearshore bars (ridge-and-trough topography) are found in shallow water where the bottom slope is gentle. They are believed to be the result of deposition of sediment by wave action. Nearshore bars in eastern Lake Michigan have been observed in shallow water on aerial photographs and on nearshore profiles (Evans [1940]; Davis and McGeary [1965]). They range from 0.5 to 1.5 m (1.6 to 5 ft) in relief and parallel the beach line for many kilometers. Some of them are not well defined, and a few divide into two bars. Separations of 90 m (295 ft) are typical. As many as four wave-lengths were observed to the maximum depth studied (6 m [20 ft]). Hough (1935) reported sand bars near Indiana Harbor trending north in water

depths of 4 to 12 m (13 to 39 ft). In a sounding and boring survey made before dredging, he found that the topography of the sand-till interface was unrelated to the bottom topography. Samples of other ridges in the Chicago area showed sand at the ridges and gravel or gravel-veneered till in the troughs (Hough, 1935). Davis and McGeary (1965) found finer-grained sand on the ridges and coarser-grained sand and pebbles in the troughs of nearshore bars. Hough suggested that the gravel was a lag deposit from wave and current action on the till and that the sand derived from the till is deposited on the bars or on the beach. He suggested that some of the ridges or bars may have been formed by similar processes when the lake level was lower, but that the presence of the lag gravel on till in the troughs and of ripple marks on the sand indicates an active process.

In June 1973, about 40 holes were drilled in the vicinity of Waukegan, Illinois, with a jet air-lift drilling device (Fraser and Hester, 1974). In the area of the two northernmost side-scan sonar tracks (fig. 10), within about 3 km (1.9 mi) of shore, 1 to 4.5 m (3.3 to 15 ft) of medium- to fine-grained sand overlies till. No linear features were observed on the side-scan sonar records in the area of these sand deposits. South of Waukegan, in the area where linear features have spacings of about 310 m (1,017 ft) (fig. 10), jet air-lift drilling encountered a little sand, generally less than 0.7 m (2.3 ft) thick, over till. Most of that area, as well as the areas east of Chicago where the linear features have been observed, is believed to be a till bottom that in some places is overlain by a thin lag of sand and gravel.

The jet air-lift drilling data tend to support the hypothesis that glacial fluting rather than wave or current processes caused the formation of the linear features. However, many sonographs of longitudinal sand furrows, sand ribbons, sand waves, gravel waves, and longitudinal sediment patches shown by Belderson et al. (1972) are similar to those of the Lake Michigan features. Since some of the linear features in Lake Michigan might be the result of very thin sand deposits on till, we believe the origin of the features to be an open question. A detailed sampling and bottom photography study might solve the problem.

CONCLUSION

A side-scan sonar and echo sounding study has delineated a variety of small-scale features on the floor of southern Lake Michigan. Circular depressions found in the muds of the deeper basin are similar to those observed in Lake Superior. In the shallower areas, sediment patches and sand ripples observed on sonographs suggest that there are strong currents acting on the lake floor. Linear ridges and troughs having a widespread occurrence in the shallower portions of southern Lake Michigan appear to be the result of wave and current action and/or glacial fluting.

REFERENCES

Ayers, J. C., 1967, The surficial bottom sediments of Lake Michigan, in Ayers, J. C., and D. C. Chandler, eds., Studies on the environment and eutrophication of Lake Michigan: University of Michigan Great Lakes Research Division Special Report No. 30, p. 247-253.

Belderson, R. H., N. H. Kenyon, A. H. Stride, and A. R. Stubbs, 1972, Sonographs of the sea floor: Amsterdam: Elsevier, 185 p.

Berkson, J. M., and C. S. Clay, 1973a, Transformation of side-scan sonar records to a linear display: International Hydrographic Review, v. 50, no. 2, p. 55-59 [English ed.].

Berkson, J. M., and C. S. Clay, 1973b, Possible syneresis origin of valleys on the floor of Lake Superior: Nature, v. 245, no. 5420, p. 89-91.

Berkson, J. M., and C. S. Clay, 1973c, Microphysiography and possible iceberg grooves on the floor of western Lake Superior: Geological Society of America Bulletin, v. 84, no. 4, p. 1315-1328.

Chesterman, W. D., P. R. Clynick, and A. H. Stride, 1958, An acoustic aid to sea bed survey: Acustica, v. 8, p. 285-290.

Clay, C. S., John Ess, and Irving Weisman, 1964, Lateral echo-sounding of the ocean bottom on the continental rise: Journal of Geophysical Research, v. 69, no. 18, p. 3823-3825.

Collinson, Charles, and J. C. Badal, 1972, Surficial sediments in southern Lake Michigan [abs.]: International Association of Great Lakes Research, Abstracts, 15th Conference on Great Lakes Research, p. 18.

Davis, R. A., and D. F. McGeary, 1965, Stability in nearshore bottom topography and sediment distribution, southeastern Lake Michigan, in Proceedings of the Eighth Conference on Great Lakes Research, p. 222-231.

Evans, O. F., 1940, The low and ball of the eastern shore of Lake Michigan: Journal of Geology, v. 48, no. 5, p. 476-511.

Fraser, G. S., and N. C. Hester, 1974, Sediment distribution in a beach complex and its application to beach replenishment: Illinois Geological Survey Environmental Geology Note 67, 26 p.

Gravenor, C. P., and W. A. Meneley, 1958, Glacial flutings in central and northern Alberta: American Journal of Science, v. 256, no. 10, p. 715-728.

Gross, D. L., J. A. Lineback, W. A. White, N. J. Ayer, Charles Collinson, and H. V. Leland, 1970, Preliminary stratigraphy of unconsolidated sediments from the southwestern part of Lake Michigan: Illinois Geological Survey Environmental Geology Note 30, 20 p.

Gross, D. L., J. A. Lineback, N. F. Shimp, and W. A. White, 1972, Composition of Pleistocene sediments in southern Lake Michigan, U.S.A.: International Geological Congress, 24th Session, Section 8, p. 215-222.

Hack, J. T., 1965, Postglacial drainage evolution and stream geometry in the Ontonagon area, Michigan: U.S. Geological Survey Professional Paper 504-3, 40 p.

Hands, E. B., 1970, A geomorphic map of Lake Michigan shoreline: Proceedings of the 13th Conference on Great Lakes Research, p. 250-265.

Hawley, E. F., and C. W. Judge, 1969, Characteristics of Lake Michigan bottom profiles and sediments from Lakeside, Michigan to Gary, Indiana: Proceedings of the 12th Conference on Great Lakes Research, p. 198-209.

Hough, J. L., 1935, The bottom deposits of southern Lake Michigan: Journal of Sedimentary Petrology, v. 5, no. 2, p. 57-80.

Hough, J. L., 1952, Fathogram indications of bottom materials in Lake Michigan: Journal of Sedimentary Petrology, v. 22, no. 3, p. 162-172.

Hough, J. L., 1955, Lake Chippewa, a low stage of Lake Michigan indicated by bottom sediments: Bulletin of the Geological Society of America, v. 66, no. 8, p. 957-968.

Lineback, J. A., D. L. Gross, R. P. Meyer, and W. L. Unger, 1971, High-resolution seismic profiles and gravity cores of sediments in southern Lake Michigan: Illinois Geological Survey Environmental Geology Note 47, 41 p.

Lineback, J. A., and D. L. Gross, 1972, Depositional patterns, facies, and trace element accumulation in the Waukegan Member of the Late Pleistocene Lake Michigan Formation: Illinois Geological Survey Environmental Geology Note 58, 25 p.

Lineback, J. A., D. L. Gross, and R. P. Meyer, 1972, Geologic cross sections derived from seismic profiles and sediment cores from southern Lake Michigan: Illinois Geological Survey Environmental Geology Note 54, 43 p.

Lineback, J. A., N. J. Ayer, and D. L. Gross, 1970, Stratigraphy of unconsolidated sediments in the southern part of Lake Michigan: Illinois Geological Survey Environmental Geology Note 35, 35 p.

Mudie, J. D., W. R. Normark, and E. J. Cray, 1970, Direct mapping of the sea floor using side-scanning sonar and transponder navigation: Geological Society of America Bulletin, v. 81, no. 5, p. 1547-1554.

Sanders, J. E., and C. S. Clay, 1968, Investigating the ocean bottom with side-scanning sonar: Proceedings of the Fifth Symposium on Remote Sensing of Environment, Willow Run Laboratory, University of Michigan, Ann Arbor, MI, p. 529-547.

Somers, L. H., and P. D. Josephson, 1968, Bottom sediments of southwestern Lake Michigan: Proceedings of the 11th Conference on Great Lakes Research, p. 245-252.

Stride, A. H., 1961, Geological interpretation of asdic records: International Hydrographic Review, v. 38, no. 1, p. 131-139 [English ed.].

Tucker, M. J., 1966, Sideways-looking sonar for marine geology: Geo-marine Technology, v. 2, no. 9, p. 18-21.

ENVIRONMENTAL GEOLOGY NOTES SERIES

STUDIES OF LAKE MICHIGAN BOTTOM SEDIMENTS

1. EGN 30. Preliminary Stratigraphy of Unconsolidated Sediments from the Southwestern Part of Lake Michigan. 1970.
2. EGN 32. Distribution of Major, Minor, and Trace Constituents in Unconsolidated Sediments from Southern Lake Michigan. 1970.
3. EGN 35. Stratigraphy of Unconsolidated Sediments in the Southern Part of Lake Michigan. 1970.
4. EGN 37. Distribution of Arsenic in Unconsolidated Sediments from Southern Lake Michigan. 1970.
5. EGN 39. Phosphorus Content in Unconsolidated Sediments from Southern Lake Michigan. 1970.
6. EGN 41. Trace Element and Organic Carbon Accumulation in the Most Recent Sediments of Southern Lake Michigan. 1971.
7. EGN 44. Distribution of Mercury in Unconsolidated Sediments from Southern Lake Michigan. 1971.
8. EGN 47. High-Resolution Seismic Profiles and Gravity Cores of Sediments in Southern Lake Michigan. 1971.
9. EGN 54. Geologic Cross Sections Derived from Seismic Profiles and Sediment Cores from Southern Lake Michigan. 1972.
10. EGN 58. Depositional Patterns, Facies, and Trace Element Accumulation in the Waukegan Member of the Late Pleistocene Lake Michigan Formation in Southern Lake Michigan. 1972.
11. EGN 69. Glacial Tills Under Lake Michigan. 1974.